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Original Article

# Anisotropic damage of titanium plates under uniaxial tension after reverse bending

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ABSTRACT

Influence of low-cycle reverse bending and the crystallographic texture on damage anisotropy of commercial titanium sheets during the subsequent uniaxial tensile tests was studied. The fourth-rank order damage tensor $D$ was used at the analysis of damage anisotropy of titanium sheets. Only the sole component $D = 1 - \sqrt{E/E_0}$ of this tensor is not equal to zero for uniaxial tension ($E_0$ and $E$ is the elastic modulus of intact material and current modulus determined from the uniaxial tensile tests, respectively). Damage caused by stresses of proof strength and ultimate strength is estimated. The damage increases with increasing of number of reverse bending cycles. The correlations of damage and mechanical properties anisotropy with the crystallographic texture are found.



## 1. Introduction

Mechanical or thermal impact is applied in modern technologies for production of metal sheet materials. Internal stress and varied structural defects occur in the metal during production processes. Internal stresses and defects hamper formation of the desired geometric shape of sheet metal, and they can damage the product [1]. Therefore, the straightening by means of machine roller straightening is applied before using of roll metal. Deformation of metal by reverse bending (RB) occurs in straightening process. Internal stresses are reduced, planar characteristics are improved, and the subsequent processing of metal is facilitated after straightening. All this has a positive effect on the quality of the finished production. Noticeable changes of structure, texture as well as of mechanical characteristics during the reverse bending previously were found, despite the relatively small deformation by the tension and compression of opposite sides of the sheet [2]. Damage in the form of micro-pores, micro-cracks and of their associations may arise at this [3]. Effects of reverse bending and texture on the anisotropy of damage accumulation

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in steel sheets during the uniaxial tension were studied earlier in [4,5]. In these studies, the anisotropy of the damage and mechanical characteristics, as well as significant correlation with the characteristics of texture was found [4,5]. The anisotropy of damage coefficient α-titanium textured sheets after cold rolled with 20% and 40% reduction was studied on results of measurements of the dynamic and static Young's modulus in [6]. It is argued that the best agreement with the experimental anisotropy gives an idea of damage tensor as tensor of 6th rank, while the tensor of the 2nd rank gives only satisfactory agreement. In [7] investigated damage coefficient of titanium alloy Ti–6Al–4V after annealing. As the measure of damage, the degradation of Young's modulus material has been used as one of the more effective techniques [8]. Series of loading–unloading experimental tests were carried out and elaborated by means of numerical models in order to build the experimental damage evolution curve. Authors [7] have received very low value of damage in the order of 0.1 for titanium alloy. Similar results were obtained by authors [8] for copper and steel. They believe that despite the popularity of the Young's modulus degradation method for evaluating damage accumulation in structural materials, there is a certain theoretical and practical difficulties in the proper application of this method to receiving of encouraging results. Therefore, according to the authors [7] there is the need of additional studies to clarify the use of aforementioned techniques. Damage coefficients in papers [6–8] were calculated according to the formula [9]

$$D = 1 - \frac{E}{E_0}, \tag{1}$$

where $E_0$ and $E$ is, respectively, the elastic modulus of intact material and current modulus that determined from the uniaxial tensile tests. Formula (1) was obtained under the assumption of an isotropic accumulation of damages in the metal [9]. At the same time, in order to calculate the damage coefficient $D$ in [10–13], an alternative variant was proposed, which seems to be more justified for the anisotropic accumulation of damages in the metal. The damage is represented by a fourth-rank tensor. Earlier it was shown that under the conditions of uniaxial tension only the single component $D$ of this tensor is nonzero [10,13]:

$$D = 1 - \sqrt{E/E_0}. \tag{2}$$

The notation in (2) is the same as in (1).

This work is aimed to find laws of influence of low-cycle reverse bending (RB) and crystallographic texture on the anisotropy of mechanical properties and damage coefficient of commercial titanium sheets by means of uniaxial tensile tests of samples carved in differ directions of titanium sheets after various numbers of reverse bending cycles.

Effect of reverse bending and texture on the damage coefficient anisotropy during the subsequent uniaxial tensile tests in sheets of titanium and its alloys earlier have not been studied.

## 2. Experimental material and procedures

Sheets of α-titanium alloy of grade 1 (3.7025) (0.15% Fe; 0.06% C; 0.05% N; 0.12% O, 0.013% H) in the delivery state after annealing at the temperature of 840 °C were used as material for the study. Initial sheets were cut on the cards of size 100 mm × 100 mm. Then these cards were subjected to the RB in the rolling direction (RD) using specifically manufactured device by roller of 50 mm diameter. The speed of the metal movement during bending was about 150 mm/s. From the initial sheet and sheets after reverse bending on 0.5; 1; 3 and 5 cycles were cut at least three batches for each cycle number for mechanical tests in the RD, the diagonal direction (DD, i.e. at an angle of 45° to the RD) and the transverse direction (TD) as well as samples for researches of the texture.

Testing machine Zwick Z250/SN5A with power sensor at 20 kN was used for mechanical tests at room temperature for samples cut in the RD, DD and TD. Samples for tests had total length and width of the working part, respectively, of 90 and 12.5 mm. The average value by at least three batches of samples in each direction was taken as the mechanical property values.

Surfaces of samples were chemically polished to a depth of 0.1 mm for the removing of the distorted surface layer before the texture study.

X-Ray diffractometer DRON-3M was used for the study of crystallographic texture. Recording of diffractograms of the sample without texture as well as textured samples was carried out in the filtered Ka Mo radiation. Then inverse pole figures (IPF) for ND of two surfaces of samples after the above-mentioned number of RB cycles were constructed. We constructed also IPF for directions, in which mechanical properties were investigated: RD, DD and TD. In order to provide a flat surface for recording of diffractograms from surfaces perpendicular to the RD, DD and TD strips of 3 mm wide were cut out in the corresponding directions. These strips then were glued to obtain the composite samples.

Investigation of microstructure was carried out at the end faces of samples orthogonal to the RD and TD by microscope MIM-7 using Web-camera E-TREK DEM 200 to output the image structure on the computer monitor.

The symmetrical damage tensor of fourth order $D$ [10–13] was used at the analysis of damage anisotropy of titanium sheets. Only the sole component of this tensor, which was calculated by Eq. (2) is not equal to zero for uniaxial tension ($E_0$ and $E$ is the elastic modulus of intact material and current modulus determined from the uniaxial tensile tests, respectively) [10,13].

## 3. Results and discussion

Fig. 1 shows IPF ND and IPF RD of titanium in the initial state as well as IPF's ND after different number of cycles of the RB. The corresponding microstructure is shown in Fig. 2.

The increased pole density on IPF's ND of the initial sheet (Fig. 1, a) covers a wide area bounded by poles $\langle 10\bar{1}5\rangle$, $\langle 10\bar{1}2\rangle$, $\langle 11\bar{2}4\rangle$. In the same time, the absolute maximum of the pole